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Theoretical Analysis on the Environmental Performance of Distributed Combined Heat and Power System

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Abstract

In this paper, the theoretical formulas of the CO_2 emissions reduction ratio of the DCHP system under different running statuses are proposed. The qualitative and quantitative analyses show that the selection of reference system and determination of the prime mover are of vital importance to the assessment of its environmental performance. At the point with electricity-heat equilibrium, the DCHP system obtains the best environmental benefit. When the heat-to-power ratio is less than the critical value, the electricity-tracking mode receives larger reduction ratio; on the contrary, the heat-tracking mode is the better option.

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Keywords: DCHP; environmental performance; heat-to-power ratio; running status; theoretical analysis

1. Introduction

As a new type of energy system which breaks the gap between the supply and demand sides, the natural gas based distributed combined heat and power (DCHP) system has been paid more and more attention in both developed and developing countries [1-2]. Among various benefits, excellent energy and environmental performances are the main reasons promoting its rapid development.

Currently, many previous studies have been reported on the energy performance of the DCHP system [3-7]. Fumo and Chamra [8] proposed the conditions a DCHP system should operate in order to guarantee primary energy savings. Pohl and Diarra [9] developed an assessment method for primary energy savings of DCHP systems by means of a primary energetic comparison of a coupled supply system with a separated supply system. Although environmental performance of the DCHP system has been mentioned

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in some of previous studies, the discussion about the nature of its environmental benefits is paid little attention.

In this study, while considering the variation of system configuration and running strategy of the DCHP system, the theoretical analytical framework of the environmental performance is developed. In addition, numerical studies are executed for various system options.

Nomenclature

Abbreviation

CERR	CO_2 emissions reduction ratio

Symbols

E	electricity load
Q	annual CO2 emissions
σ	heat-to-power ratio
φ	COP of heat pump
η	efficiency
λ	carbon intensity

Subscript

a	absorption chiller
b	direct-fired chiller unit
c	coal
e	electricity
ex	exchanged electricity
g	natural gas
h	heat
i	i-th reference system (i=1,2)
j	j-th running status (j=a,b...e)
p	power grid

2. Methodology

2.1. System configuration and running strategy

In order to illustrate the environmental benefits of the DCHP system in an intuitionistic way, two forms of common energy supply system have been selected as the reference system. In the reference systems, centralized power plant (CPP) serves the electricity load, electric heat pump (EHP) and absorption chiller and heater (ACH) supply the heating load.

As to the DCHP system, the conventional electricity-tracking and heat-tracking running strategies have been considered. The size of the prime mover is determined according to the peak load; the deficiency is supplied by the utility grid or afterburner, while the excess (EX) is sold back to the grid or let out (LO). However, the hourly energy flow of the DCHP system is not only dependent on the selected running strategy, but also on the hourly electricity and heat balances between the demand and supply sides. Therefore, in this study, while considering the running strategy and balance of supply-demand sides, five running statuses have been determined. Figure 1 shows the energy flowcharts of both DCHP systems and the reference systems.

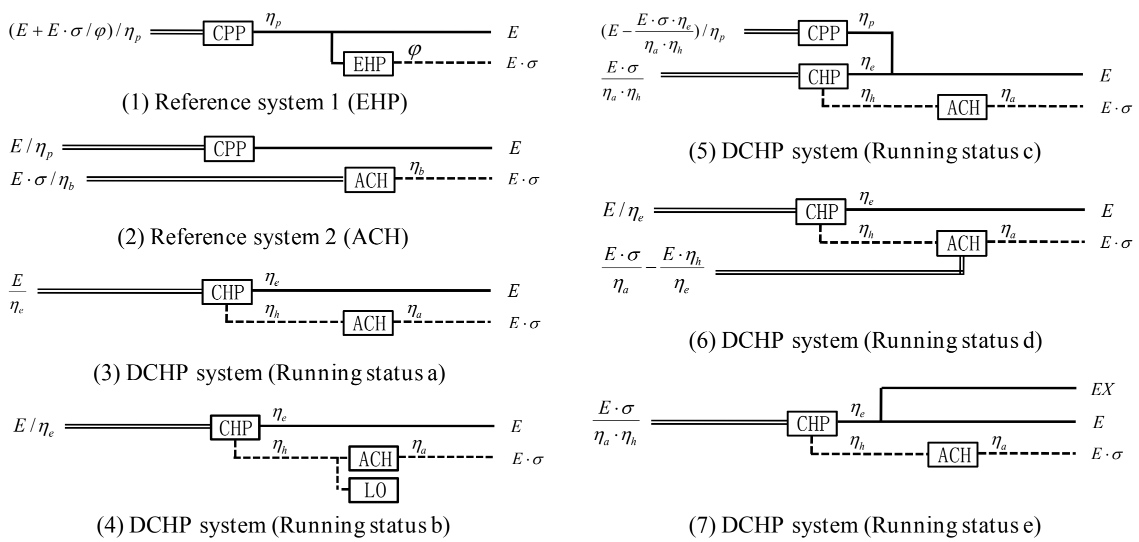

Fig. 1. Energy flowcharts of both reference systems and DCHP systems

2.2. Assessment index of emissions reduction

The environmental benefits of the DCHP system lie on two aspects: on the one hand, the overall efficiency is increased by recovering waste heat; on the other hand, fuel replacement of coal by natural gas makes the electricity be cleaner. In this study, in order to understand the environmental benefits of the DCHP system in a quantitative way, the CO_2 emissions reduction ratio (CERR) has been selected as the assessment index.

$$CERR_{ij} = \frac{Q_i - Q_j}{Q_i} \qquad \forall i = 1,2 \quad j = a,b,c,d,e \tag{1}$$

Based on the flowcharts shown in Figure 1, annual CO2 emissions of two reference systems and five DCHP systems under different running statuses can be calculated as follows:

$$Q_1 = \frac{E}{\eta_p} \cdot \lambda_c - \frac{E \cdot \sigma}{\eta_b} \cdot \lambda_g \tag{2}$$

$$Q_2 = \left(\frac{E}{\eta_p} + \frac{E}{\varphi} \cdot \frac{\sigma}{\eta_p}\right) \cdot \lambda_c \tag{3}$$

$$Q_a = \frac{E}{\eta_e} \cdot \lambda_g \tag{4}$$

$$Q_b = \frac{E}{\eta_e} \cdot \lambda_g \tag{5}$$

$$Q_c = \frac{E \cdot (\eta_a \cdot \eta_h - \sigma \cdot \eta_e)}{\eta_a \cdot \eta_h \cdot \eta_p} \cdot \lambda_c + \frac{E \cdot \sigma}{\eta_a \cdot \eta_h} \cdot \lambda_g \tag{6}$$

$$Q_d = \frac{E \cdot (\eta_a + \sigma \cdot \eta_e - \eta_a \cdot \eta_h)}{\eta_a \cdot \eta_e} \cdot \lambda_g \tag{7}$$

$$Q_e = \frac{E \cdot \sigma}{\eta_a \cdot \eta_h} \cdot \lambda_g \tag{8}$$

In addition, according to the flow chart of running status (e), the implicated CO_2 emissions of the electricity sold back to the grid can be calculated as follows:

$$Q_{ex} = \left(\frac{E \cdot \sigma \cdot \eta_e}{\eta_a \cdot \eta_h \cdot \eta_p} - \frac{E}{\eta_p}\right) \cdot \lambda_c \tag{9}$$

By combining equations (1)～(9), the CERR of the DCHP systems under five running statuses relative to two reference systems (taking electric heat pump and absorption chiller and heater as the heating source, respectively) can be deduced. Moreover, as to the running status (e), in order to evaluate its environmental performance comprehensively, it is necessary to account for the reduced CO_2 emissions related to the electricity sold back to the utility grid. Therefore, corresponding CO_2 emissions should be added to that of the reference system, while calculating the CERR value of the DCHP system under status (e). Details are shown as follows.

(1) CERR values with respect to reference system 1

$$CERR_{1a} = 1 - \frac{\varphi \cdot \eta_p \cdot \lambda_g}{(\varphi \cdot \eta_e + \eta_a \cdot \eta_h) \cdot \lambda_c} \tag{10}$$

$$CERR_{1b} = 1 - \frac{\varphi \cdot \eta_p \cdot \lambda_g}{(\varphi + \sigma) \cdot \eta_e \cdot \lambda_c} \tag{11}$$

$$CERR_{1c} = 1 - \frac{(\eta_a \cdot \eta_h - \sigma \cdot \eta_e) \cdot \varphi \cdot \lambda_c + \sigma \cdot \varphi \cdot \eta_p \cdot \lambda_g}{(\varphi + \sigma) \cdot \eta_a \cdot \eta_h \cdot \lambda_c} \tag{12}$$

$$CERR_{1d} = 1 - \frac{(\sigma \cdot \eta_e - \eta_a \cdot \eta_p + \eta_a) \cdot \eta_p \cdot \varphi \cdot \lambda_g}{(\varphi + \sigma) \cdot \eta_a \cdot \eta_e \cdot \lambda_c} \tag{13}$$

$$CERR_{1e} = 1 - \frac{\varphi \cdot \eta_p \cdot \lambda_g}{(\varphi \cdot \eta_e + \eta_a \cdot \eta_h) \cdot \lambda_c} \tag{14}$$

(2) CERR values with respect to reference system 2

$$CERR_{2a} = \frac{\eta_e \cdot \eta_b \cdot \lambda_c + \eta_p(\eta_a \cdot \eta_h - \eta_b) \cdot \lambda_g}{\eta_e \cdot \eta_b \cdot \lambda_c + \eta_a \cdot \eta_h \cdot \eta_p \cdot \lambda_g} \tag{15}$$

$$CERR_{2b} = \frac{\eta_e \cdot \eta_b \cdot \lambda_c + (\sigma \cdot \eta_e - \eta_b) \cdot \eta_p \cdot \lambda_g}{\eta_e \cdot \eta_b \cdot \lambda_c + \sigma \cdot \eta_e \cdot \eta_p \cdot \lambda_g} \tag{16}$$

$$CERR_{2c} = \frac{\sigma \cdot \eta_e \cdot \eta_b \cdot \lambda_c + (\eta_a \cdot \eta_h - \eta_b) \cdot \sigma \cdot \eta_p \cdot \lambda_g}{\eta_a \cdot \eta_b \cdot \eta_h \cdot \lambda_c + \sigma \cdot \eta_a \cdot \eta_p \cdot \eta_h \cdot \lambda_g} \tag{17}$$

$$CERR_{2d} = \frac{\eta_a \cdot \eta_b \cdot \eta_e \cdot \lambda_c}{\eta_a \cdot \eta_b \cdot \eta_e \cdot \lambda_c + \sigma \cdot \eta_a \cdot \eta_p \cdot \eta_e \cdot \lambda_g} + \frac{(\sigma \cdot \eta_a \cdot \eta_e + \eta_a \cdot \eta_b \cdot \eta_h - \sigma \cdot \eta_b \cdot \eta_e - \eta_a \cdot \eta_b) \cdot \eta_p \cdot \lambda_g}{\eta_a \cdot \eta_b \cdot \eta_e \cdot \lambda_c + \sigma \cdot \eta_a \cdot \eta_p \cdot \eta_e \cdot \lambda_g} \tag{18}$$

$$CERR_{2e} = \frac{\eta_e \cdot \eta_b \cdot \lambda_c + \eta_p (\eta_a \cdot \eta_h - \eta_b) \cdot \lambda_g}{\eta_e \cdot \eta_b \cdot \lambda_c + \eta_a \cdot \eta_h \cdot \eta_p \cdot \lambda_g} \tag{19}$$

According to the equations illustrated above, as to the same reference system, the CERR values under running statuses (a) and (e) have the same expressions, which dependent only on the technical features of the DCHP and reference systems, and have no relationship with the demand side. On the other hand, the CERR values under running statuses (b), (c) and (d) are the functions of the heat-to-power ratio of the demand side.

3. Numerical study

3.1. Parameter setting

In this study, four types of prime movers, namely, gas engine (GE), gas turbine (GT), fuel cell (FC) and stirling engine (SE) are considered [2]. The power generation efficiencies of them are assumed to be 35%, 27%, 45% and 25%; while the heat recovery efficiencies are 38%, 43%, 45% and 45%, respectively. The coefficients of performance (COP) of absorption chiller, direct-fired chiller, electric heat pump are 1.4, 1.36, 4.2, respectively, while the efficiency of utility gird is 33% [10-14]. In addition, the carbon intensities of coal and natural gas are assumed to be 25.8 kg-C/GJ and 15.3 kg-C/GJ, respectively.

3.2. Assessment of emissions reduction

Figure 2 shows the CERR values of the DCHP system with different prime movers, under different running statuses, with respect to different reference systems. Generally, the CERR values relating to reference system 1 are larger than that of reference system 2. This is mainly due to the adoption of EHP with is powered by utility grid with relatively high carbon intensity

When the DCHP system is operated under the heat-tracking mode, along with the increase of heat-to-power ratio, the running status follows the flows of c-a-e. On the other hand, as the electricity-tracking mode is employed, the running status follows the flows of b-a-d. Comparing the two running modes, it can be found that while the heat-to-power ratio is less than the corresponding value at the heat-power equilibrium point, the CERR value under electricity-tracking mode is larger than the value under heat-tracking mode; on the contrary, while the heat-to-power ratio is larger than the critical value, the heat-tracking mode may receive better environmental performance.

Furthermore, while considering the results of different prime movers, the CERR value of the fuel cell base DCHP system is the largest, followed by the value of the gas engine system.

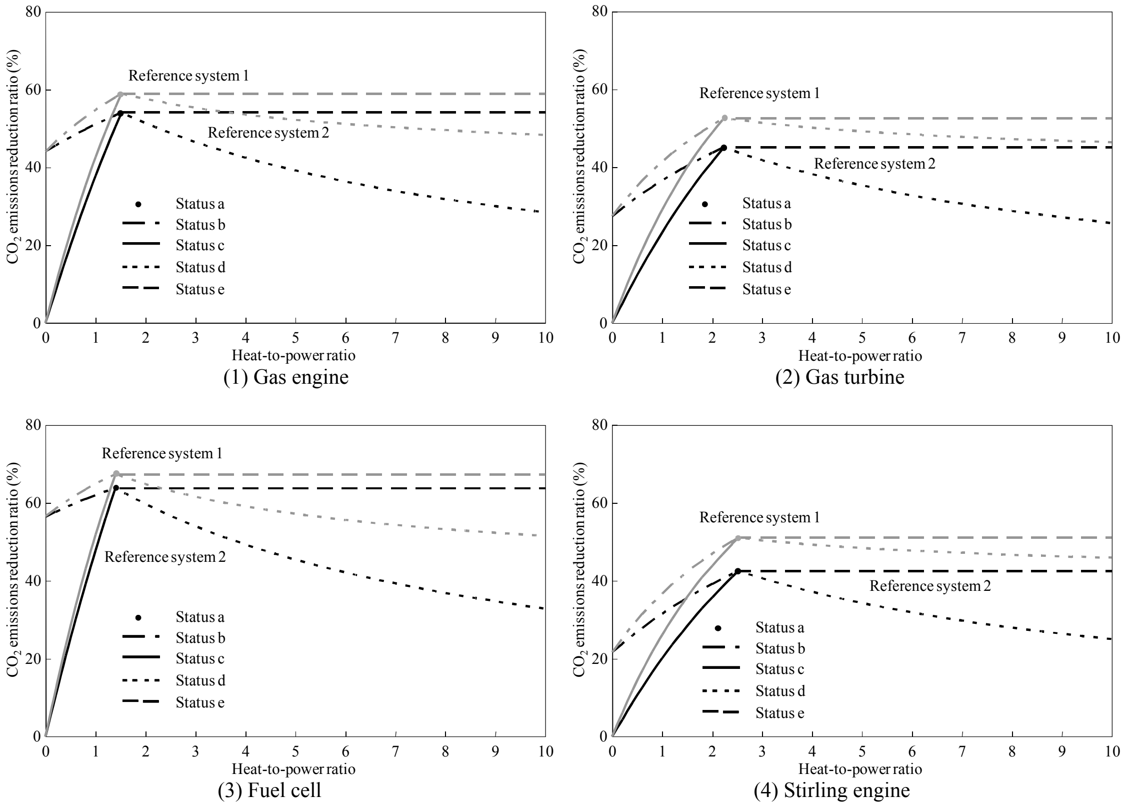

Fig. 1. CERR values of the DCHP system

4. Conclusions

In this study, based on the viewpoint of the demand side, while considering the dynamic balances of both electricity and heat between supply and demand sides, the theoretical equations of the CO_2 emissions reduction ratios under five operating statuses are proposed. The qualitative and quantitative analyses show that the selection of the reference system, as well as the determination of the prime mover and other parameters are of vital importance to the evaluation of the environmental performance of the DCHP system.

Acknowledgements

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Biography

Hongbo Ren received the Ph.D. degree in environmental engineering from the University of Kitakyushu, Kitakyushu, Japan, in 2009. In 2013, he joined Shanghai University of Electric Power as a Professor. His research interests include the fields of energy system modeling, economics and optimization.